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# CORE – Coordinated operation of integrated energy systems

*WP1 - Renewable based Energy System with P2H and P2G*

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# CORE – Coordinated operation of integrated energy systems

WP1 - Renewable based Energy System with P2H and P2G

Summary report

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# 1 Introduction

This report is the result of the work in Work Package 1 of the EUDP funded project Coordinated Operation of Integrated Energy Systems (CORE).

The current Danish government has a goal of reducing the Danish $CO_2$-emissions to 70% of 1990 levels by 2030 and going to a climate-neutral country in 2050. For the energy sector, the 2050 goal means that the Danish energy system should be independent of fossil fuels in 2050, meaning that in Denmark the renewable energy production must be able to cover the Danish energy demands. Due to the long time horizon and the uncertainties related to technology development, no specific plans are created for how the energy system should look in 2050. However, based on the Danish tradition of different actors creating energy system scenarios in order to create a democratic discussion of how the transition to such an energy system could occur, several Danish actors have in recent years created different future energy scenarios with energy systems that can accomplish the political goals. Each of such scenarios is created using the available knowledge at the given time, and different actors focus differently on different parts of the energy system based on their knowledge and needs. Examples of different actors' energy system scenarios are the Danish Energy Agency's "Energy scenarios for 2020, 2035 and 2050" from 2013 [1], the Danish Society of Engineers (IDA) "IDA's Energy Vision 2050" from 2015 [2], and Energinet's "System Perspective 2035" from 2018 [3].

The purpose of the work presented in this summary report is to utilise existing energy system scenarios from different Danish actors, thereby eliminating or reducing the potential bias from the energy scenario developers in order to analyse how different technologies could affect different types of future energy systems where renewable technologies supply all energy demands. A special focus is on power-to-heat (P2H) and power-to-gas (P2G) technologies, though the scope is not limited to these technologies. It is essential to have scenarios that both investigate the long-term 2050 energy system, but also include a shorter-term perspective, as different technologies might have different roles in a 100% renewable energy system than in energy systems with a lower share of renewable energy. In turn, this is useable for policy considerations in regards to which technologies should be implemented early and which should wait until the share of renewable energy in the energy system is higher, and which technologies are only relevant in the transition towards 100% renewable energy. Not all potential technologies are investigated in this. This summary report is based on the work presented in [4].

Energy system scenarios from "IDA's Energy Vision 2050" from 2015 [2] and Energinet's "System Perspective 2035" from 2018 [3] have been used for the analyses. The energy system scenarios in both of these reports include all energy sectors, though they detail the different parts of them differently, and both use the years 2035 and 2050 as modelling years, meaning that they have the same years for a medium- and long-term outlook.

Energinet is the Danish national transmission system operator of the electricity and gas networks. The scenarios in Energinet's "System Perspective 2035" from 2018 function as the medium- and long-term outlook for Energinet, used for planning future investments in infrastructure, developing the market design and operation strategies, and as a contribution to public and political discussions. The scenarios were developed using input data from ENTSO-E's "Ten Year Network Development Plan" (TYNDP) from 2018 to project the development in the surrounding countries. Based on TYNDP from 2018, Energinet states three different scenarios for the potential future Danish energy system to understand the consequences of the potential developments. The three scenarios in "System Perspective 2035" are:

- **Global climate action** (GCA), where Europe is ambitious concerning the green transition with a strong collaboration between the countries.
- **Distributed Generation**, also an ambitious green transition, but more national, local, and individual solutions that are used for the transition.
- **Sustainable transition** (ST), the least ambitious green transition scenario, but with increased amount of wind power and PV due to decreasing costs of these technologies.

In this work, only the ST and GCA are used, as these represent different European transition ambitions.

IDA regularly publishes scenarios for the future Danish energy system, with the first one published in 2006 and the newest published in 2020. The scenarios cover different years, with the newest "IDAs Klimasvar" currently only covering the 2030 70% $CO_2$-emission reduction target. The most recent energy system scenario covering 100% renewable energy in 2050 is "IDA's Energy Vision 2050" from 2015 that includes both a scenario for the long-term 2050 goal, but also have a medium-term scenario for 2035 [2]. As such, "IDA's Energy Vision 2050" is used in these analyses with some updates [4]. IDA's energy system scenario is developed based on the concept of Smart Energy System, in which synergies between energy sectors are exploited to increase energy efficiency and reduce costs [5]. Besides changes to the energy transformation, the scenario also includes significant energy savings at the end-users.

Besides these future scenarios, a reference model for the Danish energy system in 2020 is also made using projections from before 2020, to represent a representative model for the current Danish energy system. An overview of the scenarios used is shown in Figure 1.

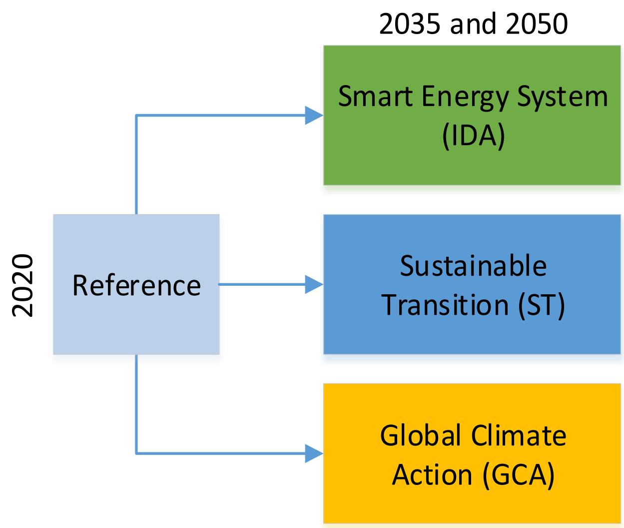


*Figure 1 – Scenarios used in the analyses*

The scenarios are used in a modelling testbed, where the scenarios are set up and adjusted to make them comparable without changing the main aspects of each scenario. More specifically, all scenarios are modelled in the same energy system modelling tool, EnergyPLAN [6], and all costs are updated so that they are using the same updated technology data. Using the modelling testbed four different focus areas are analysed:

- **Operational analyses** of the scenarios under different market price projections. Here the focus is on the operation of technologies based on the original technical setup of the scenarios.
- **Electrification** of the energy system, where the focus is on the electricity system. More specifically the following has been investigated: Industry electrification, Electricity demand flexibility, and Grid-scale electricity storage.
- **Heat sector**, where the focus is on the individual and district heating systems. More specifically the following has been investigated: Heat savings, Individual heating solution incl. heat storages, District heating production technologies, and District heating storages.
- **Renewable fuels** in the Danish energy system, where the focus is on the role and production of different renewable fuels. More specifically the following has been investigated: Biogas, Dry biomass, Electrolyser flexibility, and Electrification and electrofuels in transport.

Variations to the technologies and demands are only done in the later three focus areas. When making variations it has been ensured that sufficient energy supply is available for the energy systems simulated, by adjusting the offshore wind power capacity using a uniform method across all scenarios, so that the effects are as comparable between the scenarios as possible. Also, any scenario principles used in the development of the original scenarios are maintained. The energy system scenarios' hourly energy balances are simulated for one year of operation using an hourly temporal resolution in EnergyPLAN, where the results are mainly compared to each other in terms of total annual costs, primary fuel supply, biomass consumption, and import/export of energy.

The details of the analyses and results can be found in the full report [4], as this report only summarises the results.

# 2 Operational analyses

In this the different scenarios hourly operation is analysed without changes to the installed technologies and demands. It is found that towards 2050, where all the three scenarios go to 100% renewable energy in Denmark, the yearly operation of the CHP and power plants decrease, even in the scenarios with a significant decrease in the CHP and power plant capacity. The analyses reveal that even though the yearly operation of these plants is reduced, there are still hours where the full capacity is needed, indicating that the value of these plants shifts from being the energy produced to instead be the capacity offered. This effect is most significant in 2050, though the shift can also be seen in 2035. This indicates that markets must adapt to this change in value, as a given capacity of CHP or power plant will require more income per amount of electric energy produced to cover the long-term marginal costs. Another option is to consider these units as part of the support system or infrastructure needed in integrated renewable energy systems.

A similar situation can be seen concerning using the transmission line capacity to surrounding countries for maintaining the Danish electricity system balance. Going towards 2050 the transmission line capacity is used for import in fewer hours, however, in the hours it is utilised more of the capacity is utilised. There is also a difference in the scenarios, where ST and GCA rely heavily on the import of electricity for electricity system balance, as they have a relatively small capacity of flexible CHP and power plants, the IDA scenario has significant more CHP and power plant capacity and less transmission line capacity. Table 1 shows the transmission line capacities and flexible CHP and power plant capacity in the different scenarios.

*Table 1 – Flexible thermal electric capacity in each scenario*

| | 2020 | 2035 | | | 2050 | | |
|---|---|---|---|---|---|---|---|
| *[GW]* | **Ref. model** | **ST** | **GCA** | **IDA** | **ST** | **GCA** | **IDA** |
| **Flexible thermal plants** | 4.55 | 4.14 | 4.16 | 5.53 | 1.87 | 1.98 | 6.00 |
| **Transmission capacity** | 7.10 | 10.40 | 12.70 | 7.10 | 10.40 | 12.70 | 7.10 |

Though the transmission line capacity for import is used more at or close to full capacity in 2050, in the IDA scenario, it is used at full capacity at around 8.5% of the year, whereas in ST and GCA scenarios it is only used for import at full capacity at around 0.1% of the year. For export of electricity the transmission line capacity is utilised more at its full capacity in the ST and GCA scenarios with the full capacity being utilised at around 1% of the year in 2050.

Looking at the peak utilisation, in the 2035 versions of the ST and GCA scenarios, the transmission line capacity is only utilised up to around 70% both for import and export of electricity, indicating that the transmission line capacity in 2035 in the ST and GCA scenarios is over-dimensioned in relation to the needs of the Danish energy system. The analyses do not include the transmission of electricity through Denmark nor potential breakdowns. The analyses indicate that the transmission line capacity is needed for balancing the electricity system, though an expansion is not needed if sufficient flexible electric capacity is maintained in the Danish energy system. Also, the results indicate that the transmission line capacity is more utilised for the needs of the Danish energy system in 2050 compared to 2035 and that the full capacity of the transmission is only needed in a small part of the year, especially in scenarios where the transmission line capacity is expanded.

# 3 Electrification

Electrification is the process of satisfying end-user demands by electricity. Already many end-user demands, such as lighting, are met by electricity, though it is evident in all the scenarios that more electrification is needed in the transition towards 100% renewable energy, as the electricity demand in Denmark is set to increase from around 35 TWh/year in 2020 to 73-93 TWh/year in 2050, depending on the scenario. Examples of this include extensive use of electric heat pumps in both individual and district heating areas, a transportation sector based predominantly on electricity and electrofuels, and electrolysers for hydrogen production. The reason for the increased electrification of the energy demands is the significant increase in variable renewable electricity sources, such as wind power and PV, that goes from producing around 20 TWh/year in 2020 to around 67-8 TWh/year in 2050, depending on the scenario. From an energy production perspective, in all scenarios, the major expansion is seen in offshore wind power. With this increase in electricity demand and production, the electricity sectors role in the future 100% renewable energy system becomes even more important and is connected to many different energy sectors. This part focus on the electrification that is not related to the transport sector or the space heating and hot water consumption, as these parts are analysed in relation to the *Renewable fuels and Heating* section, respectively. As such, the electrification focus on the following parts:

- Industry electrification
- Electricity demand flexibility
- Grid-scale electricity storage

In the analyses of the electrification part, it is found that systems with low internal dispatchable power production capacity are more sensitive to external markets and external electricity prices. This is important as future electrification of the energy system is inherently connected to both internal electricity production capacity and transmission capacity. If the Danish energy system has low internal dispatchable power production, then it must also be expected that the costs of the energy system will vary to a greater extent from year to year, depending on the seasonal and yearly fluctuations of market prices. Similarly, the advantage and optimal level of electrification is also more uncertain in such an energy system.

Looking at electrification of the Danish industrial process heat demands, it is found that direct electrification of industrial process heat demands should be favoured over a fuel shift to hydrogen-based processes, due to lower costs of the energy system and higher energy system efficiency with direct electrification. From an energy system perspective, direct use of hydrogen for industrial processes should only be used where no alternative solution exists. This does not include potential gains from biproducts of the electrolyses, such as $O_2$. It is found that from an energy system perspective electromethane is not a good solution either, due to the high costs and low efficiency of the energy system, but more options are available as biogas/biomethane. Though, it should be noted that the underlying assumptions for this analysis are connected with some uncertainty, and future research should follow up on this as the technologies mature and more specific applications for hydrogen-based processes in industry are determined.

Flexible electricity demand occurs when the time of use of the demand can be shifted to another time or even be replaced by other energy sources than electricity. All the scenarios introduce many new flexible electricity demands, such as electric vehicles, electrolysis, and heat pumps with connection to heat storages. Here the focus is on flexibility of the traditional electricity demand, being the electricity demand for households and the industry sector excluding individual heat pumps. This can, e.g. be flexible use of washing machines or refrigeration. In all the scenarios, around 10% of the traditional electricity demand is set as flexible, with most of it being flexible within one day. It is found in the analyses that increased flexibility of the traditional demand can contribute to increased integration of renewables, especially for energy systems with few other flexibility options in the internal electricity production mix, mainly as the flexibility helps reduce electricity demand in peak hours. The effects of this are limited to the available capacity and this type of flexibility only allows the demands to be moved within a relatively short period, typically max. a week, and flexibility for longer periods is also needed. Uncertainties remain in relation to the actual achievable flexibility amount and the potential investment costs needed. However, the energy markets should be designed in such a way as to allow for flexible use of electricity by consumers, especially in scenarios with high reliance on import and export of electricity, as a supplement to the new flexible electricity demands.

Grid-scale batteries are often discussed as a way of allowing for higher utilisation of variable renewables in the electricity system. Li-ion batteries are discussed as they have seen a decrease in price, as they are the main components of many appliances and electric vehicles, and they have a relatively high round-trip efficiency compared to other battery technologies. In this study, the use of li-ion batteries as grid-scale batteries is found to be a very costly approach for integrating variable renewable electricity sources, even with the most optimistic price projections for li-ion batteries. Li-ion batteries concerning grid-scale applications may be useful for other purposes such as back-up capacity or short-term balancing and frequency regulation if no other cheaper alternatives exist, though in an integrated future Danish energy system it is unlikely that the need for such grid-scale batteries is relevant to any significant extent. Li-ion batteries does, however, serve an essential role in relation to the transport sector to allow for the use of electricity in vehicles.

Other grid-scale battery technologies are being developed worldwide, and some of these might allow for a significantly lower investment cost than li-ion or other batteries. In this some preliminary analyses are done for one of these technologies, being high-temperature rock bed storages. In rock bed storages electric energy is used to heat rocks to high temperatures that allow for the extraction of the energy stored as heat to be used in a turbine. The technology is still in development, and the potential implementation potentials in the energy system requires more research, though here the technology is tested to be used as a supplement for combined cycle gas turbines that includes a steam turbine component. With the application of the rock bed storages examined here, the competitiveness is largely dependent on the ability to replace fuel usage in CHP and power plants in the system, which, inherently, has fewer and fewer operation hours. In these preliminary analyses, high-temperature rock bed storages seem economic feasible as a cheaper alternative to li-ion batteries for electricity storage, allowing low investment cost short-term storage of energy from variable renewable electricity sources. However, this needs to be verified in future analyses as improved technical data becomes available, and as such, the results presented in this is related to a high degree of uncertainty.

# 4 Heating

The heating sector here is defined as all space heating demands, hot water consumption demands, and losses in the district heating systems. As such, industrial process heat demands are not investigated in this section.

In all the scenarios the heating sector continues to be an important energy sector in Denmark, as even with heat savings that are introduced in the different scenarios the heat demand still accounts for a large share of the end-user energy demand. The scenarios also include changes to the heating solutions used, both in relation to the production of heat but also for storing heat. In this, the following are analysed:

- Heat savings
- Individual heating solution incl. heat storages
- District heating production technologies (CHP units and heat pumps)
- District heating storages

Heat savings are found to reduce the total annual costs of the energy system, mainly by reducing fuel consumption, but only up to a certain point, thereafter the costs of introducing more heat savings are higher than the gains. In relation to energy system costs the optimal level of heat savings is found to be approximately 32% compared with the average consumption per $m^2$ in 2010. Heat savings also result in reduced biomass consumption, which continues to decrease linearly as more heat savings are implemented. The reduction in biomass consumption is mainly due to decreased biomass consumption for district heating fuel boilers and biomass gasification, as the individual biomass boilers only account for relatively small energy demand. As the biomass amount that can be used for a sustainable future energy system is likely limited, heat savings until around 42% could provide reductions in biomass consumption at a relatively low cost. Going from 32% to 42% heat savings increases the total annual cost of the system by less than 0.2% of total annual costs of the IDA scenario for 2050 but reduces the biomass consumption by about 3.5% of the total biomass consumption of the IDA scenario for 2050. As such, introducing heat savings is important for both reducing the total annual costs of the energy system but also to reduce the biomass consumption of the energy system.

In the three scenarios, the technology for individual heating is changed from being delivered by fuel boilers to instead being mostly delivered by electric-driven heat pumps. This decision is analysed, and it is found that if biomass boilers were used instead of electric-driven heat pumps for individual heating, both the biomass consumption and the total annual cost of the energy system would increase. This conclusion is regardless of analysed energy system scenario as well as the market prices for fuel and electricity. It is also found that solar thermal heating can help to reduce the use of biomass of the energy system, though solar thermal is only expected to be a supplement. As such, individual heating should mainly be supplied by electric-driven individual heat pumps in a future energy system based on 100% renewable energy. Having individual heat storage technologies in connection with the heat pumps and solar thermal can reduce the biomass consumption of the energy system but only up to a certain point, depending on the amount of other flexible electricity demands in the scenario, though research has shown that from an energy system cost perspective only low-cost individual storage options should be considered.

Currently, CHP plants deliver a large share of the Danish district heating production. However, as shown in the operational analyses the operation of CHP plants is expected to be different in future 100% renewable energy systems. As such, it is analysed how different thermal plant technologies would affect the energy system. The tested technologies are combined cycle gas turbine (CCGT), simple cycle gas turbine (SCGT) and large Wood Pellets Extraction plant. It is found that the high electric efficiency of the CCGT provides the system with the lowest costs and lowest biomass consumption. The CHP capacity’s effect on the biomass consumption has also been tested, by removing the CHP capacity in the test of the three technologies, thereby changing them from CHP plants to power plants. Though the overall differences are minor, it is found that the use of large-scale CHP units might not be necessary for keeping the biomass consumption at low levels, as long as the replacement power plants are highly efficient and sufficient other low-biomass consuming heat sources for district heating, such as heat pumps, are available in the system.

Electric-driven heat pumps are extensively used for district heating production in all the scenarios. The effect of these units is analysed by increasing and decreasing the capacity of these with different replacement technologies. This is first tested without changing the capacities of the other district heating technologies, and here it is found that for the total annual costs the optimal sizing is very dependent on the price projections used. In relation to biomass consumption, increasing the heat pump capacity decreases the biomass consumption, though the effect of this is most significant at low levels of heat pump capacity. Similar conclusions are found if geothermal heat is used as a replacement technology for district heating production, though the variations due to price projections are reduced by having this technology as replacement. In the ST and GCA scenarios for 2050, which have the lowest capacities of large-scale CHP capacity, using CHP capacity as a replacement for the district heating-based heat pumps is also investigated. Here it is found that CHP capacity as a replacement only reduces the total annual costs of the energy system at high electricity market price levels, except if increased CHP capacity in Denmark would result in reduced capacity of transmission line capacity, in which case the CHP would also reduce the total annual costs at the medium electricity price levels. As such, having internal flexible CHP capacity in the energy system seems to make it possible to reduce the total annual costs of the energy system, and as shown in other analyses it would also stabilise the total annual costs in relation to changing international electricity market prices.

Short-term storages for district heating are also analysed, and it is found that in most cases, completely removing short-term storages increases both the total annual costs and biomass consumption of the energy system. For total annual costs, this is less obvious in scenarios with many different district heating production technologies and high levels of excess and geothermal heat, where the value of short-term storages is lower. Though, the analyses presented in this are expected to undervalue the benefits that short-term storages can have locally and in the daily operation of individual district heating systems.

# 5 Renewable fuels

Going towards 100% renewable energy also means changing the fuels used to renewable alternatives. Some is expected to be changed to direct electrification, such as electric vehicles and electric-driven heat pumps, however, fuels will likely still be needed in the energy system for different purposes, such as long-haul road transport, maritime navigation, aviation or gas for CHP, power plants or industry. In this part, the roles of the following are analysed:

- Electrolyser flexibility
- Electrification and electrofuels in transport
- Biogas
- Dry biomass

Generally, it is found that producing any type of liquid or gaseous renewable fuels is more expensive and less efficient than direct electrification, so priority should always be given to direct electrification where possible. Electrofuels can supply the demands in the parts of the transport sector where direct electrification cannot. Despite their increased resource consumption (compared to direct electricity use), electrofuels may also act as a mean to store electricity as chemical energy using electrolyses. The results show considerable potential for flexible operation of electrolysers, providing sufficient hydrogen storage exists. The need for hydrogen storage in this respect means that there is a balance to strike between the flexible operation of electrolysers and the energy system costs. In this, it is found that the optimal balance for the Danish energy system is somewhere between 2.5 and 4 days of hydrogen storage combined with an electrolyser capacity of about 1.6-1.7 times the minimum needed capacity. This result is especially sensitive to the cost of hydrogen storage.

For the transport sector, it is found that liquid electrofuels provides lower energy system and fuel costs than gaseous electrofuels. Electromethanol has the lowest energy system costs, albeit like the results for electromethane until the cost of vehicles is added in the equation. Generally, methanol provides greater flexibility regarding storage and readiness to be upgraded to other fuels, namely jet fuels, which is a more complicated and energy-intensive process if it would be produced from methane. Fischer-Tropsch fuels may be an alternative if methanol-to-jet fuel pathways does not show sufficient technological maturity in the future.

The production process of electrofuels has a large impact on the energy system. Producing bio-electrofuels from biomass gasification indicates more significant overall biomass consumption but increases the efficiency of the energy system compared to producing $CO_2$-electrofuels. That occurs as bio-electrofuels use both electrolytic hydrogen and the hydrogen in biomass, while $CO_2$-electrofuels can only use electrolytic hydrogen. Both types of electrofuels are necessary for the future energy system despite the higher costs of $CO_2$-electrofuels as the fuels are limited by biomass availability and available $CO_2$-sources.

Biomass is pivotal to balance the future energy system in the periods when variable renewable electricity sources are not sufficient. The results of the analysis indicate that syngas from biomass gasification will be a crucial fuel in combination with biogas both used for power, heat, or industrial purposes, at lower costs than electrofuels. Biogas should always have priority due to the lower cost, but since the agricultural sector outputs limit it, it must be complemented by syngas. Biogas and syngas should both be used without further processing if possible, due to the high additional costs for upgrading, in dedicated grids or locally. Figure 2 illustrates the levelised cost of electricity for flexible power plants using any of the for types of fuels at different feedstock prices compared to the cost of electricity produced from offshore wind, indicating that the least amounts of syngas should be used for the purpose of electricity generation. In addition, maximising on the use of lower-cost bio-electrofuels has reduced use of biomass for electricity generation allowing the energy system to be more resilient to external electricity prices.

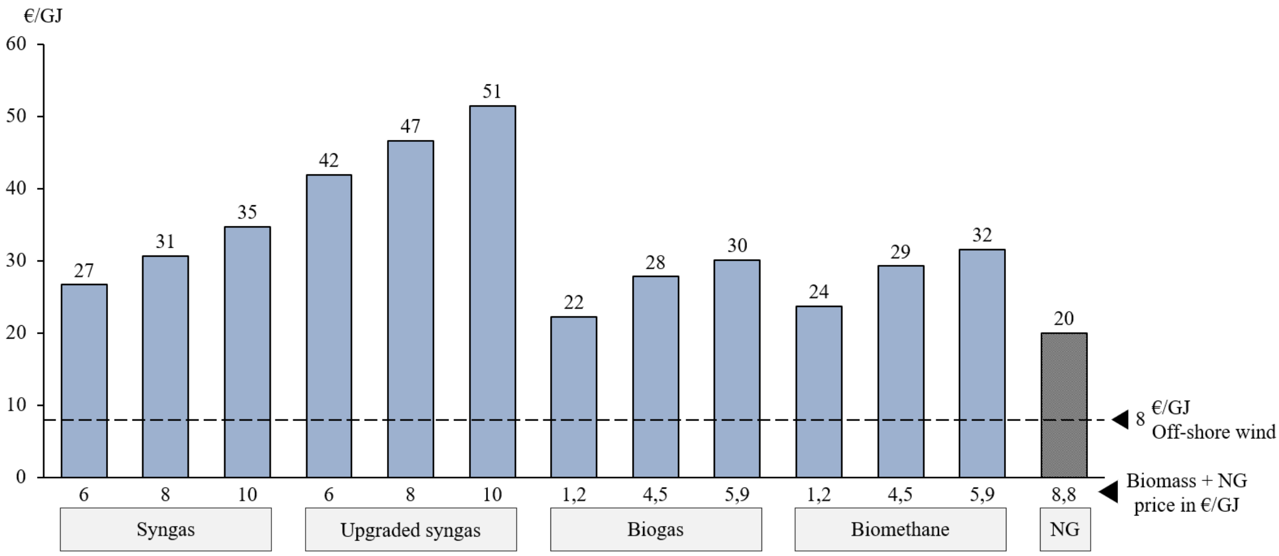


*Figure 2 - The levelized cost of electricity for a CCGT in extraction mode with 4,000 hours of operation hours with different fuels options and prices, compared to the offshore wind electricity price, all at 2050 cost and efficiency levels* [7]

It is found that biomass conversion technologies and electrofuels will have a crucial role in future energy systems but that the biomass consumption should be kept within the sustainable boundaries. Biomass gasification combined with methanol production as primary fuel should be prioritised for the transport sector where direct electrification is not possible. $CO_2$-electrofuels may be an add-on technology combined with carbon capture and utilisation from the remaining large carbon emitters to produce high value-added fuels, such as for aviation. A balance between producing fuels for transport and syngas for power production should be found, as syngas and biogas are the few fuel options for electricity, heat, or industry sectors in a 100% renewable energy system for Denmark.

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